The focus of coverage for this issue is a progress report for the ESPRC III-V Central Semiconductor Facility (CF) at the University of Sheffield. It is home to many interesting activities and recently was awarded a major grant to help it stay at the leading edge of III-Vs materials and device development.

The Sheffield Central Facility for III-V Semiconductors (CF) was established in 1978 and is now the main provider of III-V semiconductor materials for the UK scientific community. It acts as a centre of excellence in the fields of growth, materials characterisation and device processing, its primary role being in the supply of a wide range of well-characterised III-V epitaxial layers to the university community. The service also includes a comprehensive range of prototype device fabrication.

The CF located within the Department of Electronic and Electrical Engineering at the University of Sheffield is unique owing to its dual approach of being a centre of academic excellence and serving fellow UK institutes with materials and device processing. There are currently 28 EPSRC grants for which material supplied by the CF has been authorised, a very clear indication of the important role it plays in UK III-Vs.

Roy Szweda
Associate Editor

III-Vs excel at Sheffield's Central Facility

Sheffield's Central facility is about to undergo a planned expansion thanks to a ESPRC award for 4 years of continuous support. This includes new staff or returning staff such as Mark Hopkinson who will be overseeing the CF MBE development including the addition of a third MBE machine and John David who will be taking up an academic post.

Sheffield recently announced the award of a substantial new grant covering the period from July 2002 to June 2006. It covers the purchase of significant capital items which will enable the CF to stay at the forefront of III-V development. In addition, an extra RA has been awarded to help with the increasing workload in the device fabrication laboratory, particularly now that electron beam lithography is available to the CF and in the near future a focussed ion beam system will also be accessible for CF use.

The main capital items awarded include an MOVPE reactor for AlGaInAsP and dilute nitrides. It has also specified the reactor to include all of the MR350 phosphide capability as well as several channels for the growth of GaInAsN based on the reagents t-butylarsine, t-butylhydrazine and 1,1 dimethylhydrazine. A 6x2 inch reactor (equivalent to 2x3 inch) will allow for a change-over to 3 inch wafers as and when required, as well as providing large uniform areas for the growth of VCSEL and other resonant cavity structures. It also specified the inclusion of the reagent drier technology pioneered at Sheffield, and employed on the existing Quantax and MR350 reactors, in the new reactor.

Another major addition will be a research scale 'production geometry' MBE reactor. A new state-of-the-art, MBE system is to be purchased to address, proactively, future UK university requirements for MBE epitaxial wafers of the highest quality, with state-of-the-art uniformity and wafer sizes up to future industry standards.

MOVPE: opto

The CF has a two-pronged approach to MOVPE which can be conveniently split into III-V optoelectronics and GaN.

CF has long been interested in MOVPE structures over a wide range of compound semiconductors. Recent developments include AlGaInAsP and the dilute nitrides. For the former they have been developing for high T0 980nm lasers. In the latter, high capacity oxygen gettering is being developed to remove moisture from substituted hydrazines.

These and other features are going to be consolidated into one reactor, says John Roberts, Senior Research Scientist and in charge of the Department of Electronic Engineering's MOVPE activities. The upgraded reactor will enable highly uniform structures using substrate rotation of up to 3-in substrates. This will be important for devices such as VCSELs and other resonant cavity structures.

This reflects the CF's emphasis not only on research but also on collaborative development for pilot production for its diverse customer base. So too the small scale production geometry MBE machine which has such features as a horizontal wafer orientation, multiple platens and replaceable shrouding for quicker turnaround and contamination control more akin to those machines used in epiwafer companies.

On the schedule for development are long wavelength InGaAs-based quantum dots, antimonides and dilute nitrides.

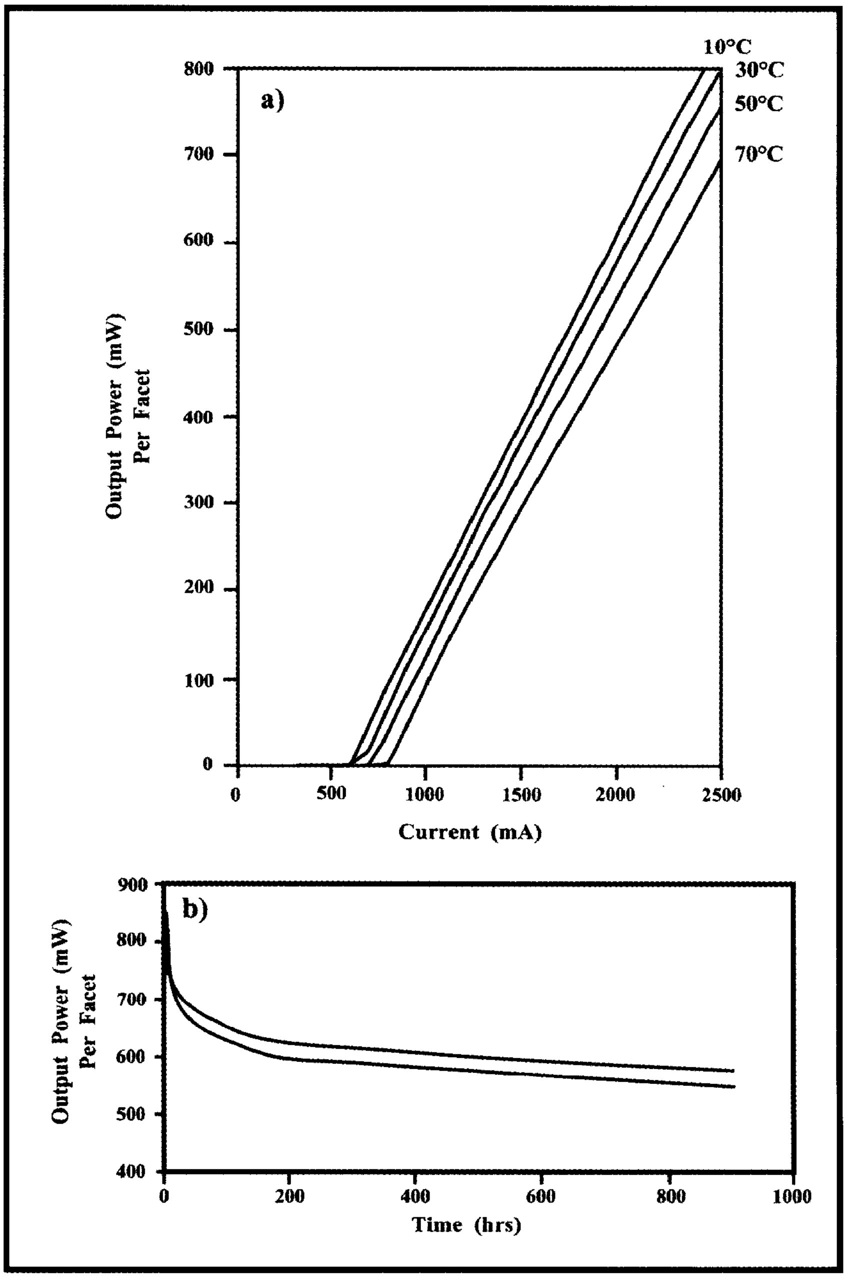
For example, the MOVPE systems at the CF have been used to grow materials for red VCSELs and strain-balanced MQW structures for thermovoltaic devices. These illustrate how the CF works in collaboration with other UK universities such as Cardiff and Glasgow. Another example is the preparation of MQ barriers in red lasers for Cardiff.

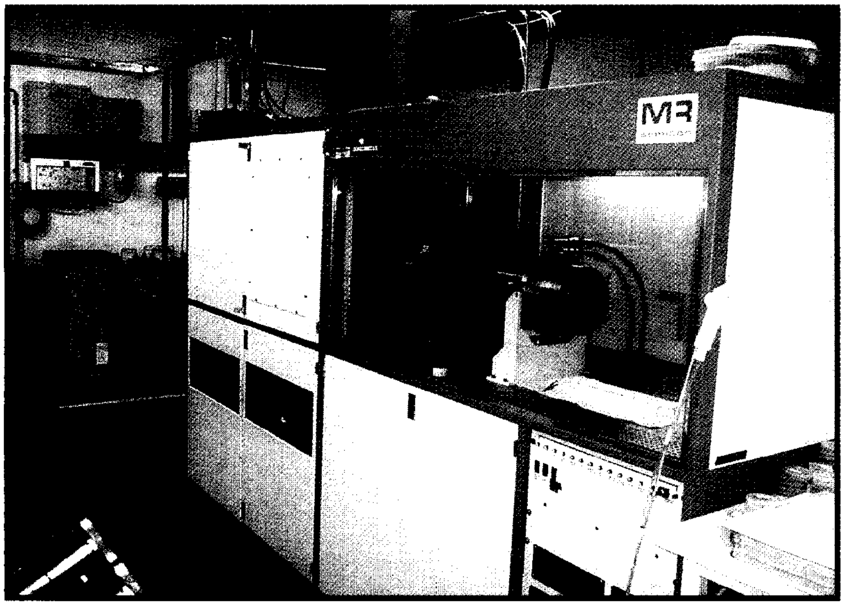
The Central Facility growth component covers a wide variety of structures, including both InGaAs(P)-based structures on InP substrates for 1.5 micron devices, and (Al)GaInP-based structures on GaAs substrates for visible (630-670 nm) devices. The range of structures covered includes optical modulators, transverse and vertical laser structures, strain-balanced MQW structures for emitter and detector applications, and wide band gap AlGaInP-GaAs HBTs. Nearly all of these structures are highly complex, containing a large number of layers of different composition, all of which need to be controlled accurately.

An example of the progress being made at CF's MOVPE facility was provided by a paper presented at the recent ICMOVPEX meeting in Berlin. Dr Roberts and his colleagues reported on their correlation of the CW characteristics of two large optical cavity (LOC) diode lasers with the structural quality of their partially strain balanced DQWs, see Figure 1.

"Increasing the lasing wavelength from 1070 nm to 1118 nm has resulted in increased roughening for the QW interfaces and an apparent lowering of internal quantum efficiency," says Dr Roberts. "When equivalent uncoated devices were compared, the threshold current was 35% larger for the 1118 nm device. However, the slope efficiency for the two devices only differed by 7% at time zero. The life-time performance at 1070 nm was in excess of 4600 h at 1.5 W with the operating current increasing by only $2x10^{-5}$ /h.

Figure 1.
The lifetime performance of the 1118 nm device was measured using uncoated facets. The degradation rate was $1.4x10^{-4}$ /h over 900 h and ~600 mW output per uncoated facet.





MR350 reactor used for phosphorus-based alloys.

We believe this to be the highest power and correspondingly longest lifetime reported for this wavelength."

The CF's MR350 is a low pressure (150 Torr) MOVPE reactor designed for operation with phosphorus-containing compounds and has established itself as a very reliable source of high quality structures across the range of the InGaAs(P), (Al)GaInP, InP and GaAs materials systems.

Working with industry

In addition to national academic collaborations the CF is working with local commercial suppliers.

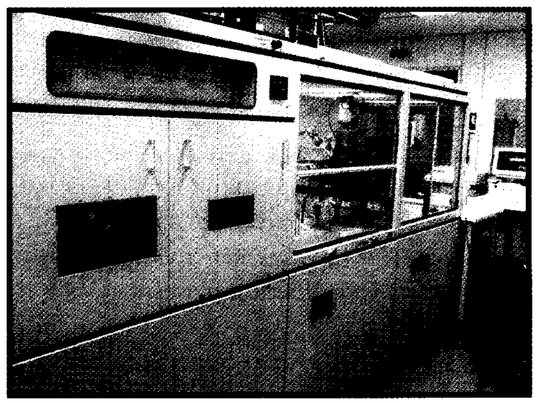
An example of this kind of industrial collaboration is a project to investigate residual oxygen contamination of InAlGaAs SQW high power laser diodes which the Department of Electronic and Electrical Engineering carried out with Epichem Ltd. As part of continuous improvements in precursor quality, recent data highlight the improved minority carrier performance and low oxygen content of AlGaAs structures. Trials focused on developments with the EpiPure grade of products, particularly TMI and TMA. With the introduction of an improved in-house analytical technique at Epichem, the refinement of process parameters has been successful in lowering impurity species in both TMI and TMA to record levels. Trials in growth have confirmed the improvement.

An 808 nm GRINSCH laser structure was grown by MOVPE at Sheffield University with new EpiPure product TMI. The room temperature PL data was obtained using a few mW of 633 nm HeNe laser light from the as-grown 50 mm wafer. The SQW of 96 A InAlGaAs was roughly 1.6 microns below the surface with a heavily Zn-doped 0.2 micron GaAs cap layer. A significant point is that until recently no RT PL could be achieved from such as-grown structures. Instead, etching to just above the QW was the only method of assessing luminescence.

UK III-nitrides

Sheffield has a programme of research on a range of III-nitride topics and once again collaboration plays a key part. For example it is working on the mechanisms of stimulated emission in nitride quantum wells in collaboration with the Optoelectronics Group in the Department of Physics at Cardiff University and for this project the samples were grown at the CF. It is also working on the InGaAlN system for short wavelength optoelectronic and high temperature electronic applications as part of Sheffield's contribution to the UK Nitride Consortium.

Quantax MOVPE reactor with automatic vacuum loadlock.



Peter Parbrook is a Senior Lecturer at Sheffield and is responsible for the CF's dedicated reactor for the III-nitrides. "This was installed in 1999 and is a Thomas Swan GaN MOVPE reactor. The growth of nitride-based semiconductor materials, including GaN, AlGaN and InGaN is carried out in a modern vertical 'showerhead' reactor which provides excellent growth uniformity over a wide range of growth conditions."

Work to date has been on developing the growth process. Already, good quality uniform material has been grown with a thickness variation of better than 3% across the entire usable part of the wafer.

"Doping of GaN both p- and n-type has been achieved, as has the growth of InGaN quantum wells," Dr Parbrook adds. "As a result bright blue and green LEDs have been fabricated. An optical output power of over 1 mW has been achieved for

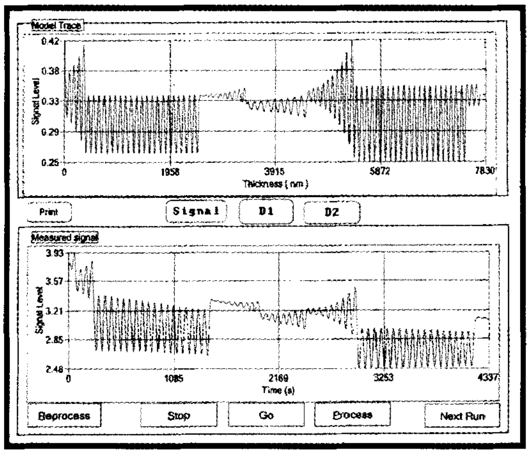


Figure 2. Modelled (top) and measured (bottom) laser reflectometry trace for a GaAs/AlGaAs quantum cascade laser.

a bare device. The InGaN composition was controlled by varying the well growth temperature."

Work on AlGaN has yielded HFET structures which show state-of-the-art 2-deg mobilities of over 1000 $cm^2V^{-1}s^{-1}$ with sheet carrier densities of $1x10^{13}cm^{-2}$. Transistor device characteristics have been observed with a transconductance of 80 mS/mm for a device length of 1.1 micron. In characterisation the CF has a frequency doubled (229 nm) CW argon ion laser to measure AlGaN and narrow GaN/AlGaN quantum wells.

Strong MBE efforts

As well as having state of the art capabilities in MOVPE, the CF also has a strong effort underway in MBE. Earlier this year it welcomed back Dr. Mark Hopkinson who is now in overall charge of the MBE facility comprising two MBE machines and a new machine due soon.

The oldest MBE machine provides a facility for the growth of selected material combinations based on the InGaAlAsP system, and uses conventional Group III metal sources in combination with Group V valved-cracker cells. The use of these latter cells now provides much-improved control and switching of the As and P dimer fluxes, leading to the controlled growth of both

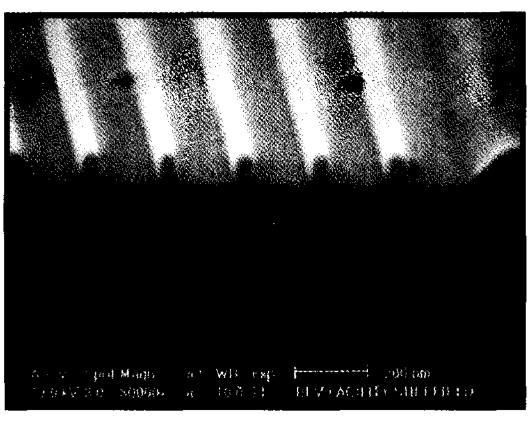


Figure 3. 200 nm period EBL grating in PMMA.

composition-stable mixed Group V alloys (eg InGaAsP, InAsP) and also improved As-P containing interfaces (e.g. InGaAs/InP, GaAs/GaInP). Si and Be are used for p and n-type dopants, respectively.

Recent important enhancements in capability relating to accurate control of cell temperatures and also automatic correction of shutter-induced flux transients resulted from installation of a new computer system. Additionally the installation of a new CCD camera-based RHEED-oscillation monitoring system has facilitated the necessary high-accuracy flux calibrations required for reproducible growth in the InGaAlAsP system.

A significant MBE growth development has been the establishment of a UK-leading capability relating to the growth of piezoelectric InGaAs/GaAs/AlGaAs device structures on (111)B oriented GaAs substrates. Detailed and systematic growth experiments have led to an understanding of the influence of growth parameters on the material and device properties so that samples can be provided with reproducibly good characteristics.

Device processing

The CF has a well equipped device fabrication lab having state-of-the-art process and characterisation equipment such as Karl Suss contact mask aligners with 0.7 mm resolution, two thermal and one e-beam evaporators for contact deposition, a PECVD, RIE, RTP, Dektak, ellipsometer and a probe station attached to a Tektronix curve tracer.

The PECVD system is used for deposition of silicon nitride, silicon dioxide and silicon oxynitride layers, as well as the deposition of Bragg stack mirrors with alternating layers of silicon nitride and silicon dioxide.

The two RIE systems are fitted with an Intellemetrics laser reflectometry system, which permits real time monitoring of etch depth, see Figure 2. "This is of great benefit as often a wafer of a given epitaxial structure is only etched once before moving on to a different structure," says Geoff Hill, CF's Senior Research Scientist in charge of the Device Lab. "One of the etchers is configured for etching of GaAs/AlGaAs structures and GaN based materials, while the other is set up for etching of InGaAs/InP structures and antimony containing compounds."

The CF recently purchased a Raith 150 e-beam lithography system. It is situated close to the III-V CF so it is available for projects requiring

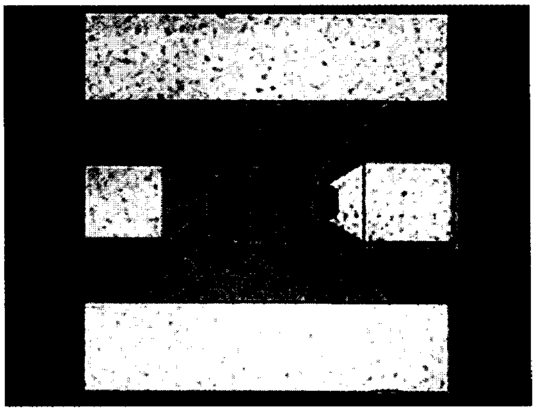


Figure 4a. AlGaN/GaN HFET

nanometre scale patterning. Feature sizes of below 40 nm have been written with field stitching errors of 30 nm, see Figure 3.

The III-V Centre will shortly be taking delivery of an Oxford Plasma Technology load-locked ICP etch system to etch GaAs/AlGaAs and GaN structures, a high temperature chlorine based etch process for InP, as well as methane hydrogen etching for InGaAs/InP and antimonide etching

Device supplied to EPSRC customers cover a wide range of opto and electronic devices fabricated in a number of different material systems. These range from simple structures such as PIN photodiodes, resonant tunnelling structures and Hall bars, to more complex structures such as QC laser structures, VCSELs, HEMTs, quantum dot rib waveguide lasers and LEDs. As an example of the diversity of material systems used for some of these devices, LEDs have been fabricated in InGaN/GaN (blue and green), InGaP/InGaAlP/GaAs (red), InAsSb/InAsSbP/InAs (mid-infrared 4.6 mm emission), AlGaInP/AlGaAs/GaAs (green and yellow) and conjugated polymer materials (green).

Many new developments have taken place recently, says Dr Hill. "Quantum cascade lasers have achieved world-class performance and, for some structures, world beating performance. Diamond detector arrays for radiotherapy dosimetry have been developed in collaboration with the Physics Department at Sheffield, de Beers and Weston Park Hospital in Sheffield. Also, HEMT devices which can be fully switched off, with drain currents of below 1 nA, have been developed for Surrey University. These are for use with pixel arrays of GaAs X-ray detectors, so that the pixels can be individually addressed."

III-nitride devices in opto and electronics also have been made. These include LEDs emitting

Standard Unpassivated HFET

Gate length = 0.6 - 0.7μm

Gate width = 40μm

Ids ~ 790 mA/mm

G_m~ 180mS/mm

Vgs = +1Vg, step: -1V

Figure 4b. Data for an AlGaN/GaN HFET

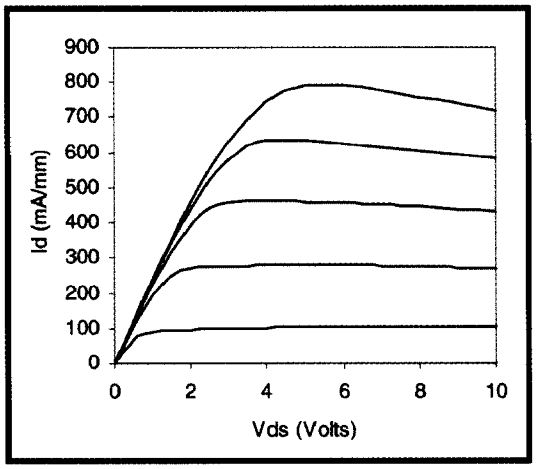


Figure 4c. I-V trace of an AlGaN/GaN HFET

1 mW and 0.7 mm gate length AlGaN/GaN HEMT structures with transconductances of 180 mS/mm see Figure 4.

Conclusions

The Sheffield CF is unique and has a long history of good service to fellow UK universities. This will be able to continue and expand thanks to new developments. CF will ensure that its expertise and capabilities match the future needs of the UK III-V community. For epi materials and devices it will also service academics through 'pump priming' so researchers can test proof of concept before applying for full funding.

Well suited to future needs of the UK III-V community via new EPSRC awards, the CF is equipping to carry out its long-term plans out to 2006. With new equipment and new staff it will truly be among the best and most competitive to support the nationwide progression of a wide range of key III-V research and pilot-production.

On the CF website you can read more than we can cover here. One of the better maintained sites, it includes a quarterly newsletter available as a PDF download. See: http://www.shef.ac.uk/eee/cf/main.html